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An Assessment of Inlet Total-Pressure Distortion Requirements for the Compressor Research Facility

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NOTICE

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A study was conducted to determine the potential requirements for inlet total-pressure distortion in the Wright Laboratory Compressor Research Facility (CRF). The study included types and levels of distortion of interest, generation methods, instrumentation, and test techniques. Cost comparisons of various options were generated. Based on this study, it was determined that time-variant distortion testing is beyond the scope of the CRF mission and that screens should continue to be used to generate steady-state distortion.

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List of Symbols

AIP	Aerodynamic interface plane
K	Distortion sensitivity
MPR	Multiple-per-revolution element
N	Number of instrumentation rings
PAV	Ring average total pressure
$PAVLOW$	Average total pressure of low total-pressure region for a ring
$PFAV$	Face average total pressure
$P(\theta)$	Total pressure at any angle θ for a given ring
Q	Number of low-pressure regions
$\Delta PC/P$	Circumferential distortion intensity element
$\Delta PR/P$	Radial distortion intensity element
ΔPRS	Loss in surge pressure ratio (at a constant corrected mass flow)
θ	Circumferential location in degrees
θ^+	Extent of high-total-pressure region
θ^-	Extent of low-total-pressure region

Subscripts

i	Ring number
k	Low-pressure region number

1 Introduction

Aircraft gas turbine engines are often subjected to nonuniform inlet conditions which can include both spatial and temporal distortions of inlet total temperature and total pressure. Operation of the compression system with distorted inflow typically results in reduced aerodynamic performance, reduced stall margin, and increased blade stress levels (possibly increased to the point of failure).

The primary cause of temperature distortion at the engine inlet is weapons discharge. Although stable engine operation is always important, weapons firing is a small fraction of the overall mission profile and is not a part of many missions. Total-pressure distortions, however, exist during all phases of aircraft operation, and most of the distortion research conducted to date has been directed at understanding total pressure effects. For this reason, this report will focus exclusively on total-pressure distortion.

Steady-state total-pressure distortions are the result of having some object disrupt the flow of air entering the engine. This disruption may be caused by an open weapons or landing gear bay door, by a noncircular aircraft inlet, or by devices placed in the inlet to reduce the radar signature of the engine. The pressure distortion pattern which exists at the inlet plane of an operating aircraft gas turbine engine is actually time-unsteady, but is evaluated as a steady-state pattern with turbulence superimposed; the turbulence level is measured as P_{RMS} in the frequency range from 0 to 1000 Hz. In addition, transient pressure distortions are produced when aircraft maneuvers change the flow of air relative to the engine.

A large, complex facility is required to accurately test engine response to the combination of steady, turbulent, and transient distortion patterns anticipated from flight maneuvers. In addition to the engine support facilities, a full-scale inlet is needed to house the engine and a large secondary air supply system is needed to generate flight

speed and altitude conditions relative to the inlet. Because the distortion patterns generated by flight maneuvers are of short time duration, high response instrumentation is needed to determine engine response to the simulated maneuvers. This type of full-scale testing is prohibitively expensive in most cases.

To provide a more cost-effective test program, estimates of the most severe distortion patterns expected from the anticipated combination of inlet design and flight maneuvers are made. The engine or compression system is then tested with a steady-state distortion pattern that is at least as severe as the worst-case flight distortion. If no stability problems are encountered in these steady-state tests, then it is unlikely that operational problems will be encountered. For this reason, the remainder of this report, and the use of the term "inlet distortion" herein, will focus on spatial variations of time-averaged inlet total pressure during compression system component testing.

Because of the emphasis currently placed on reducing the radar signature of the inlet/engine face and on increased maneuverability, future engines will be subjected to higher levels of inlet distortion than have previously been encountered. Accordingly, increased emphasis should be placed on distortion testing during propulsion system development. CRF compression system testing has often included phases defining performance sensitivity to inlet pressure distortion, but the facility has relied upon the test article vendor to supply the distortion pattern requirements and the distortion generation hardware.

An investigation has been conducted to define a distortion testing methodology for the CRF. Recommendations are made for the distortion patterns which should be tested, the hardware which should be used to generate the patterns, and the aerodynamic performance variables which should be scrutinized. Based on current estimates, the cost of performing distortion testing in the CRF is presented.

2 Nomenclature

It is recommended that the CRF adopt the Society of Automotive Engineers Aerospace Recommended Practice, ARP 1420 (Reference 1), for all nomenclature relating to inlet total-pressure distortion. Although these descriptors are by no means unique, they will provide a consistent method of quantifying distortion patterns and compression system sensitivity to them. Because this is the current industry standard, it is expected that test article vendors will find this nomenclature acceptable. If other nomenclature is requested, the conversion from ARP 1420 descriptors is straightforward. This situation may arise if a future test article is one for which distortion testing has been done in the past and the existing database is in another format.

The following sections list the ARP 1420 definitions which are recommended to measure and describe inlet total-pressure distortion patterns.

2.1 Aerodynamic Interface Plane (AIP)

The following guidelines are suggested for the selection of the physical location of the interface plane:

a. The AIP should be located in a circular or annular section of the inlet duct.

b. The AIP should be located as close as practical to the engine-face plane. The engine face plane is defined by the leading edge of the most upstream engine strut, vane, or blade row.

c. The AIP should be located so that all engine airflow, and only the engine airflow, passes through it.

d. The AIP location should be such that engine performance and stability are not measurably changed by the interface instrumentation.

2.2 AIP Rake/Probe Array

A probe array should be agreed to among the involved parties and should remain invariant throughout the propulsion system life cycle for all testing. For components which have already undergone distortion testing, the probe array for future CRF tests should be the same as the array used during previous testing to allow meaningful comparison of results. For components which have not previously undergone distortion testing, it is recommended that 8 equiangularly spaced rakes be used, with 5 probes per rake location at the centroids of equal areas, as shown in Figure 1. The rake/probe array should be located as close as practical to the AIP.

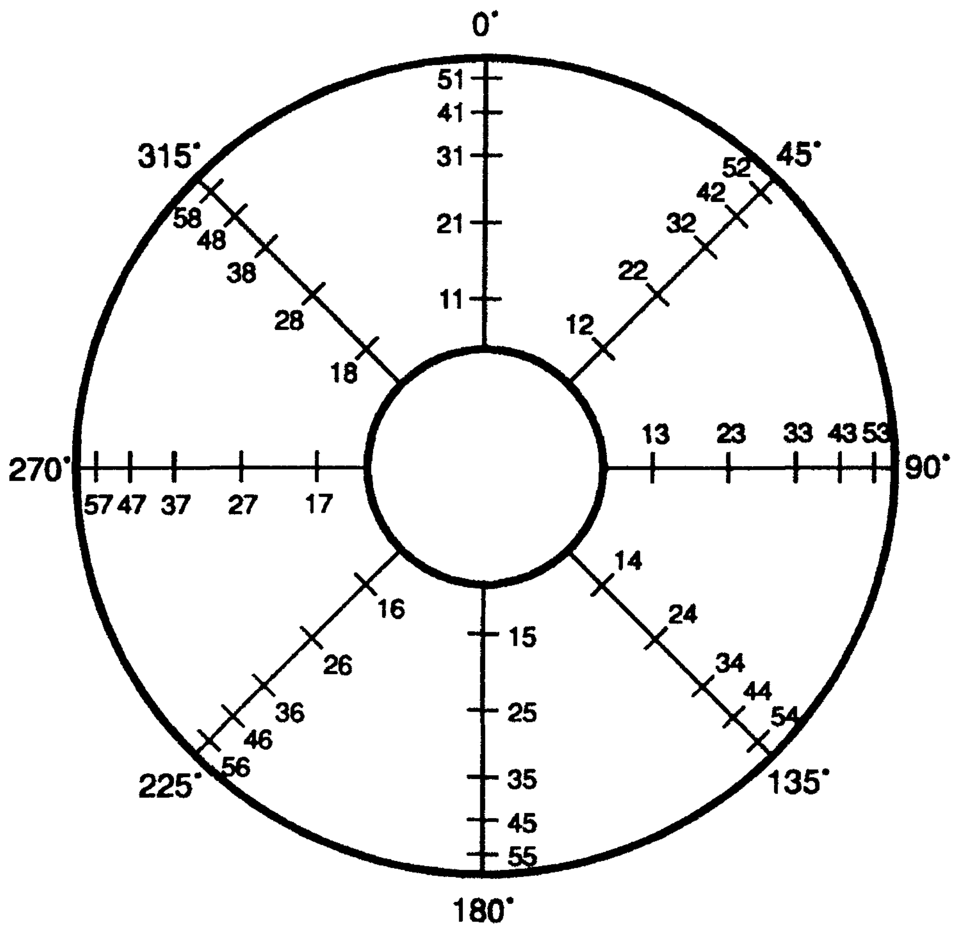

Figure 1. Probe Orientation - View Looking Forward

2.3 Distortion-Descriptor Elements

The distortion-descriptor elements are used to describe the distortion at the AIP. The fundamental element is the set of pressure-probe readings that are used to describe the pressure distribution at the AIP. Circumferential and radial distortion elements (obtained using the pressure probe readings) are described on a ring-by-ring basis.

2.3.1 Circumferential Distortion Elements

Circumferential distortion is described on a ring-by-ring basis in terms of intensity, extent, and multiple-per-revolution elements as follows. Typical pressures for the probes in the i^{th} ring for a one-per-revolution pattern are shown in Figure 2.

Intensity: The circumferential distortion intensity element, $\Delta PC/P$, describes the magnitude of the pressure defect for each ring and is obtained by linear interpolation of the pressures in a given instrumentation ring. Positive values of intensity indicate a

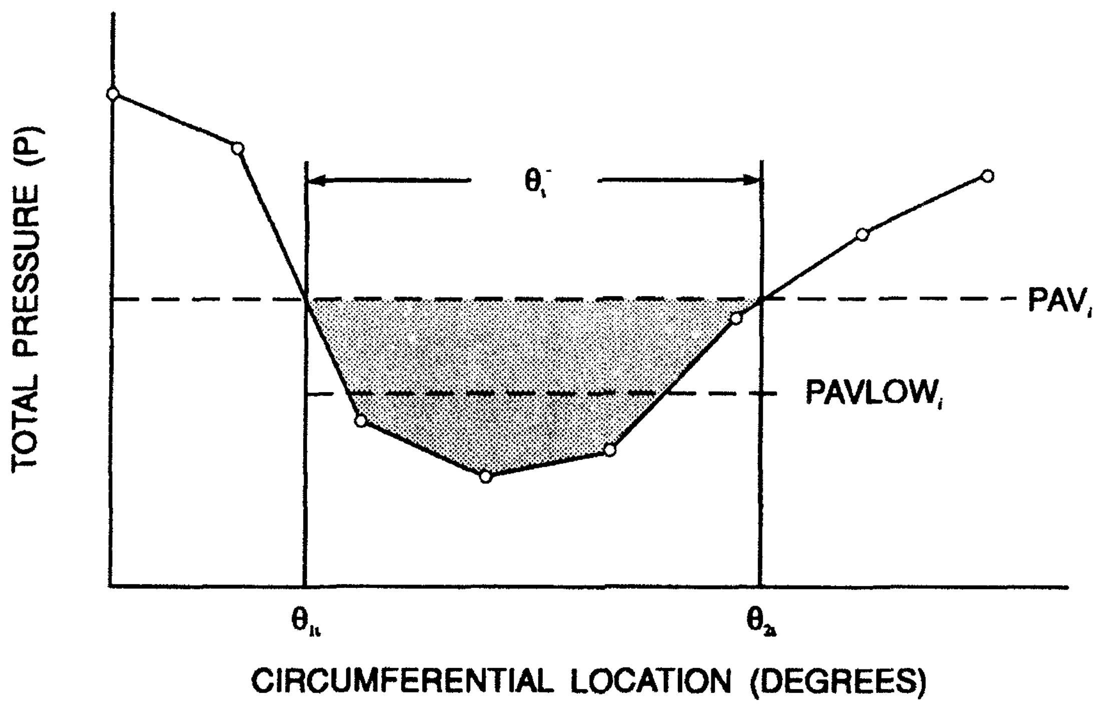

Figure 2. Ring Circumferential Distortion for a One-Per-Rev Pattern

region of pressure below the face average pressure. For the i^{th} ring:

$$\text{Intensity} = \left(\frac{\Delta PC}{P}\right)_i = \frac{PAV_i - PAVLOW_i}{PAV_i} \tag{1}$$

where:

$$PAV_i = \frac{1}{360}\int_0^{360} P(\theta)_i \, d\theta = \text{Ring average pressure} \tag{2}$$

$$PAVLOW_i = \frac{1}{\theta_i^-}\int_{\theta_i} P(\theta)_i \, d\theta \tag{3}$$

$P(\theta)_i$ is a function resulting from a <u>linear fit</u> between the data points.

Extent: The circumferential distortion extent element for each ring, θ_i^-, is the angular region, in degrees, in which the pressure is below ring average pressure and is obtained by linear interpolation of the pressures in a given instrumentation ring:

$$\text{Extent} = \theta_i^- = \theta_{2_i} - \theta_{1_i} \tag{4}$$

Multiple-per-rev: The circumferential distortion multiple-per-revolution element, *MPR*, describes the number of low pressure regions for each ring and is obtained by linear interpolation of the pressures in a given instrumentation ring. Figure 3 shows a pattern with two low-pressure regions separated by two high-pressure regions of extent θ_{1i}^+ and θ_{2i}^+. If the pattern has low-pressure regions circumferentially separated by high-pressure regions with extents less than or equal to θ_{min}^+, it is considered as an equivalent one-per-revolution low-pressure region. A value of θ_{min}^+ of approximately 25° is suggested in the absence of other information. For a pattern with Q low-pressure regions per ring and $\theta_{ik}^+ \le \theta_{min}^+$, $MPR = 1$ and the extent is calculated by.

$$\text{Extent} = \theta_i^- = \sum_{k=1}^{Q} \theta_{ik}^- \tag{5}$$

For the pattern shown in Figure 3:

$$\text{Extent} = \theta_i^- = (\theta_2 - \theta_1)_i + (\theta_4 - \theta_3)_i \tag{6}$$

The intensity for a multiple-per-revolution pattern is calculated by Equation 2, but the area-weighted average low-pressure region is calculated by:

$$PAVLOW_i = \frac{1}{\theta_i^-} \sum_{k=1}^{Q} \int_{\theta_{ik}} P(\theta)_i \, d\theta \tag{7}$$

For a pattern with Q low-pressure regions per ring and $\theta_{ik}^+ \geq \theta_{min}^+$, the intensity, $\left(\Delta PC/P\right)_i$ is the $\left(\Delta PC/P\right)_{ik}$ corresponding to the maximum value of:

$$\left[\left(\frac{\Delta PC}{P}\right)_{ik} \times \theta_{ik}^-\right] \tag{8}$$

The value of the circumferential extent, θ_{ik}^-, is value of which corresponds to the above region, k, of maximum intensity.

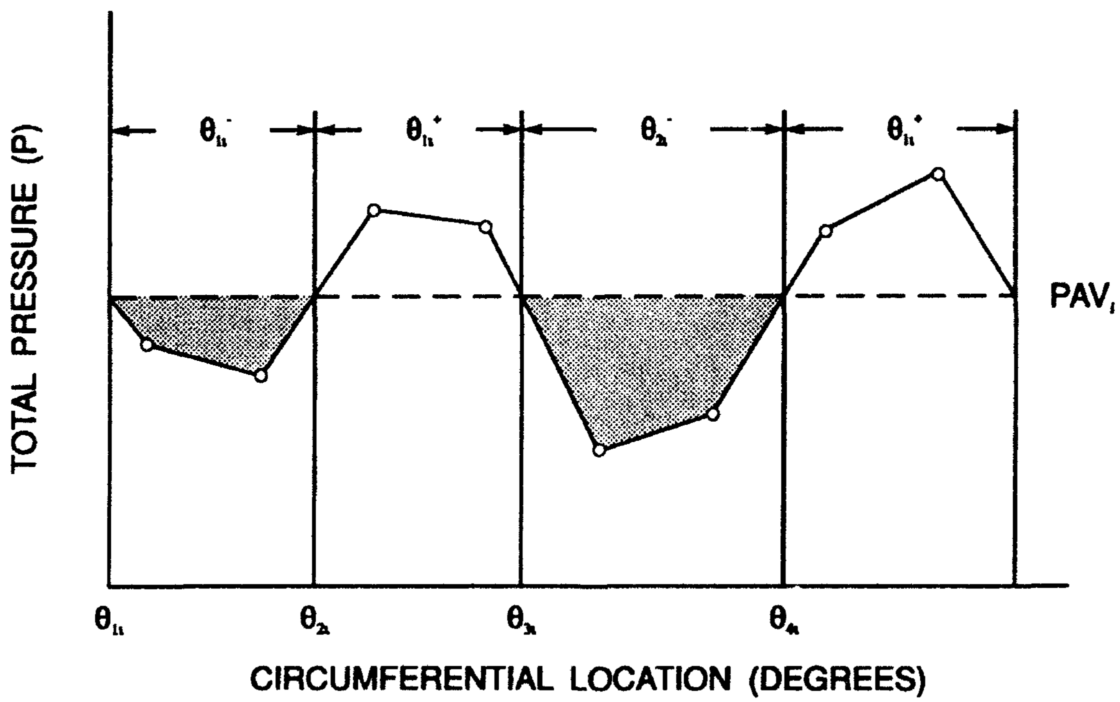

Figure 3. Ring Circumferential Distortion for a Multiple-Per-Rev Pattern

The multiple-per-revolution term is defined as the number of equivalent low pressure regions, the equivalence being based on the ratio of the total integrated area beneath PAV_i in Figure 3 to the largest single area beneath PAV_i. This is given by:

$$\text{Multiple-per-revolution} = MPR_i = \frac{\sum_{k=1}^{Q}\left[\left(\frac{\Delta PC}{P}\right)_{ik} \times \theta_{ik}^{-}\right]}{\max\left[\left(\frac{\Delta PC}{P}\right)_{ik} \times \theta_{ik}^{-}\right]} \tag{9}$$

2.3.2 Radial Distortion Elements

The radial distortion intensity element, $\Delta PR/P$, is defined as the difference between the face-average pressure and the ring-average pressure, divided by the face-average pressure. Both positive and negative values of radial intensity are considered; positive values reflect a ring average pressure that is below the face average.

A typical tip-radial distortion pattern is shown in Figure 4. For the i^{th} ring, the radial intensity is given as:

$$\left(\frac{\Delta PR}{P}\right)_i = \frac{PFAV - PAV_i}{PFAV} \tag{10}$$

where PAV_i is calculated from Equation 2.

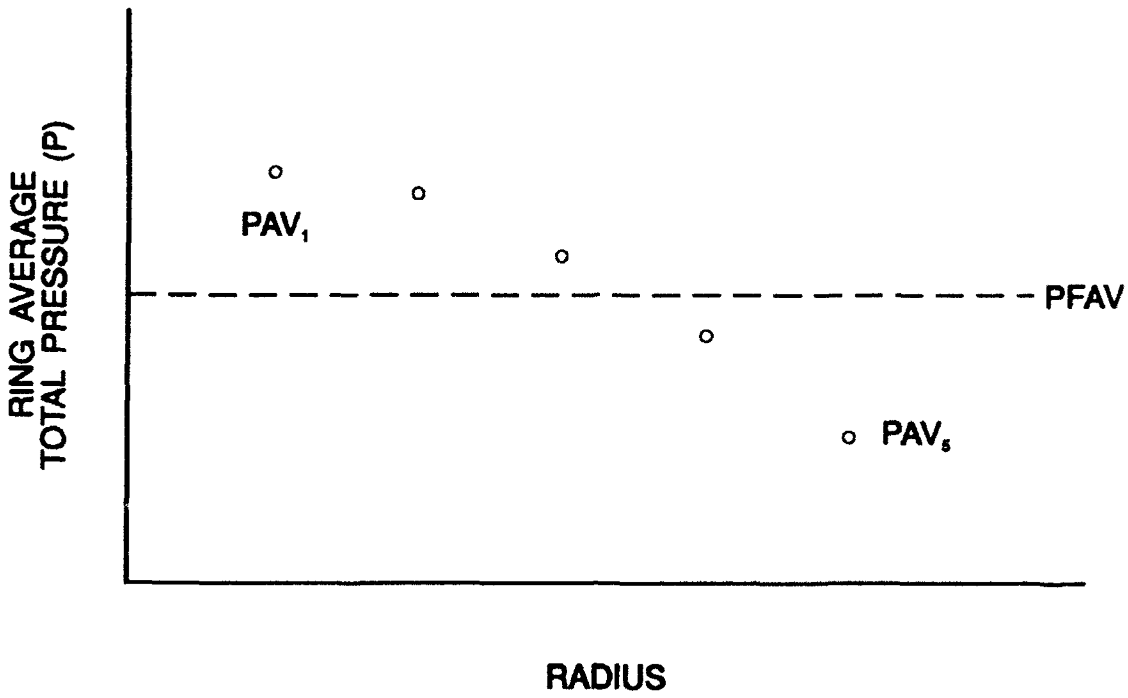

Figure 4. Typical Tip-Radial Distortion Pattern

3 Development of a Distortion Testing Program

A general distortion testing program has been formulated for use in the CRF. The distortion testing methodology, recommendations for patterns and intensities to be tested, and the measurements to be taken are presented in turn.

3.1 Distortion Testing Methodology

The overall focus of distortion testing is to assure that the compression system will allow the engine to meet overall propulsion system goals. For an entirely new engine and airframe, the process begins with preliminary estimates of the distortion patterns which the inlet will develop and for the distortion tolerance the engine will have, both based on the historical experience of the respective manufacturers. In the concept and early design stages, there is a significant uncertainty in both of these estimates as shown in Figure 5. To reduce the risk of encountering operational problems, scaled inlet

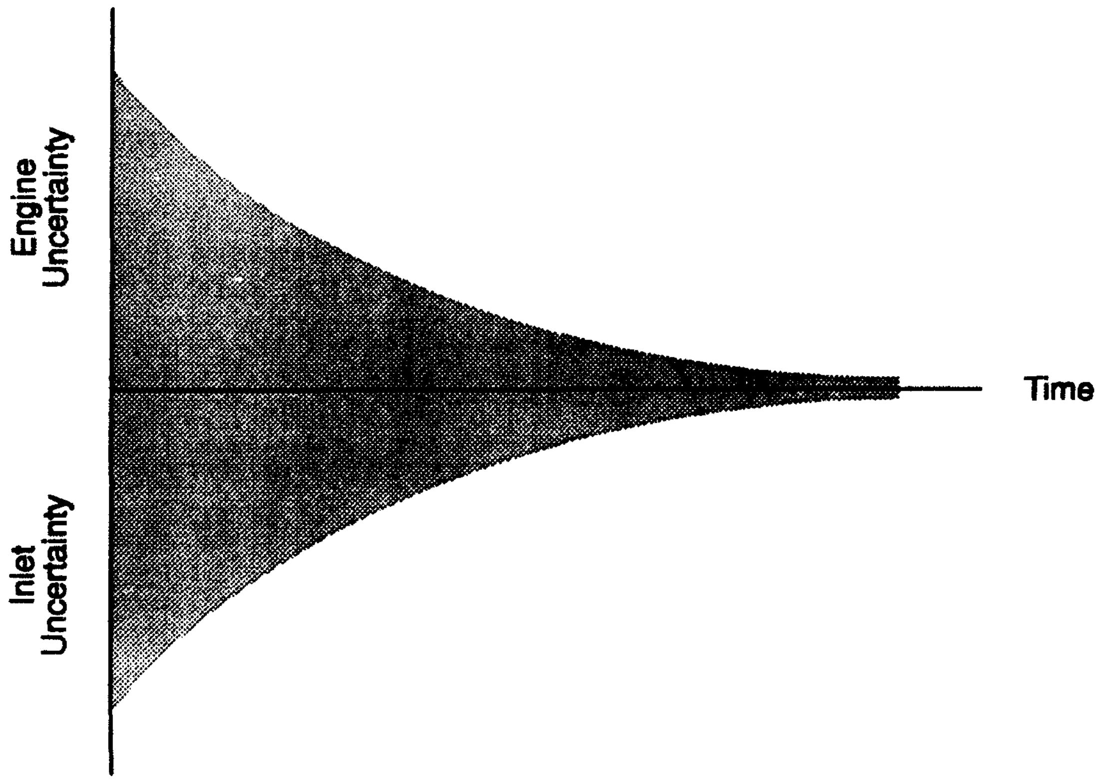

Figure 5. Timeline of Inlet/Engine Compatibility Uncertainty

tests are conducted to determine the distortion patterns which can be expected from flight maneuvers and these patterns are tested on compression system components.

Typically, distortion testing is conducted by creating steady-state inlet-distortion patterns which are as severe as the most severe transient distortion which is expected to be encountered anywhere in the flight envelope. The results of this initial compression system testing are then used to identify and correct any areas of possible engine/inlet incompatibility. This is an iterative test/evaluation process that is intended to reduce the uncertainty in the stability assessment to an acceptable level, thus avoiding the expensive and time-consuming redesigns required when an in-flight problem is encountered.

If a new or upgraded engine is being considered for use in an existing airframe, the testing process is fairly straightforward because the inlet characteristics are already known with a high degree of certainty. If an advanced research component is to be tested for distortion sensitivity, however, the decisions regarding distortion patterns and intensities to be tested are unclear because the aircraft inlet characteristics are unknown.

By testing with classical patterns (180° one-per-rev circumferential, pure hub-radial, and pure tip-radial distortions) and increasing the intensity until the stability limit is reached, it is possible to gain a quantitative understanding of how a compression system will respond to various distortion patterns. This will typically involve multiple data points for a given pattern to probe both sides of the stability limit. Correlations of the form (Reference 2):

$$\Delta PRS = \sum_{i=1}^{N}\left[KC_i\left(\frac{\Delta PC}{P}\right)_i + KR_i\left(\frac{\Delta PR}{P}\right)_i + C_i\right]\times 100 \qquad (11)$$

have been developed to correlate distortion intensity with loss in compression system surge margin, ΔPRS, where N is the number of instrumentation rings, KC is the circumferential distortion sensitivity, KR is the radial distortion sensitivity, and C is an

offset term. Unfortunately the sensitivity terms are extremely hardware dependent and a universally applicable form of Equation 11 is beyond the state of the art.

If sufficient resources are available, it is desirable to test with composite distortion patterns as well. By testing a few composite patterns with intensities near the stability limit, it is possible to make estimates of the sensitivity of a compression system to arbitrary distortion patterns, as shown in Figure 6. Although the exact shape of this curve is unique to every compression system, the general shape is similar for all.

Whether testing classical or composite distortion patterns, predicting the stability limit is not a simple process. Estimates can be made based on blade profile, aspect ratio, stage loading, and other factors, but extrapolating from the existing database to a new design has proved difficult. Because a great deal of empirical knowledge is used in this estimation, the test article vendor is currently best prepared to estimate the distortion intensity at which instability is expected.

In addition to having an adverse effect on aerodynamic performance and stability,

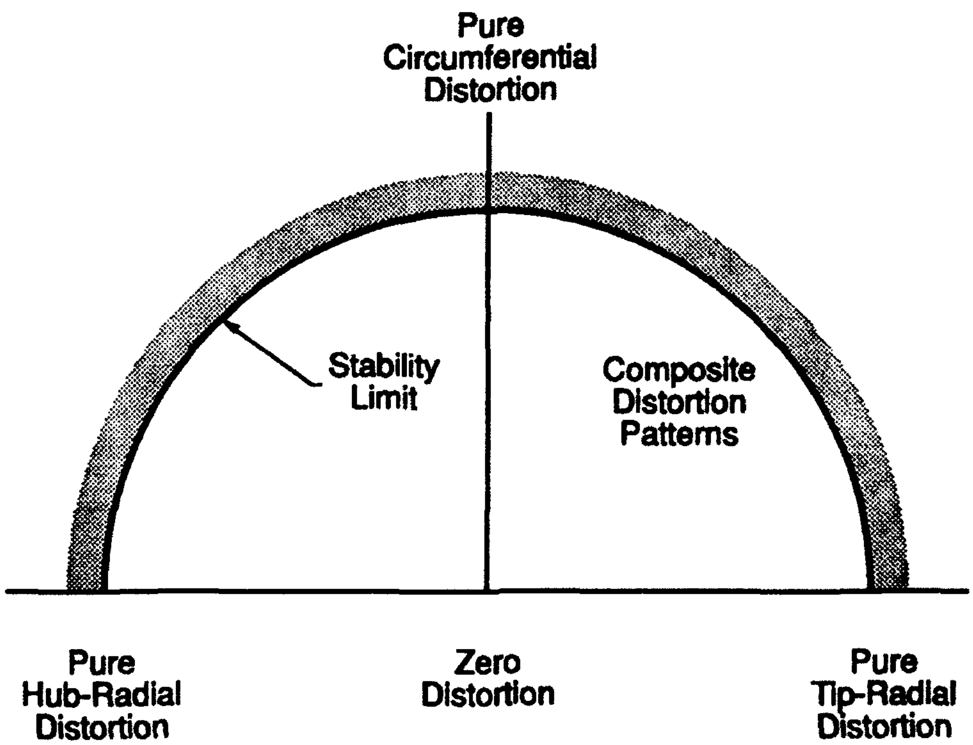

Figure 6. Compression System Tolerance to Inlet Distortion

inlet distortion affects compression system aeromechanics. Because an airfoil can experience a short-term excursion to high incidence without flow separation, the high-frequency components of distortion do not affect compression system stability. These high-frequency components do, however, affect the mechanical integrity of the blades, and distortion patterns of higher frequency than 2/rev can cause catastrophic blade failure. This mode of failure can happen in steady-state operation, far from the surge point. In actual flight operation, however, multiple-per-rev (MPR) distortion patterns are the result of aircraft maneuvers and are short-lived. Although steady-state testing with MPR distortion patterns does not approximate an actual flight condition, it is a useful tool for aeromechanics research.

The majority of previous distortion research has focused on the mass-averaged aerodynamic performance of the component or engine and has ignored the internal effects. When a circumferential distortion pattern is present, the rotor will see differing flow incidence angles as it passes through regions of alternating high and low pressure. Assuming the distortion is not severe enough to cause flow separation, more work will be done on the high-incidence air than the low-incidence air, and a spatial temperature distortion will be generated at the rotor exit plane. The pressure distortion present at the inlet plane will propagate through the compressor at the local acoustic speed, and the temperature distortion generated as a result will propagate at the convected speed of the air. In addition, both distortion patterns will shift circumferentially in the direction of rotor rotation.

The transmission of these distortion phenomena through the engine can have a significant effect on stability. If a distortion pattern is imposed on the tip region of a fan, the distorted exit flow will travel down the bypass duct and the spatial irregularities are not critical. If a distortion is imposed on the hub region, however, the distorted exit flow becomes the inlet flow for the core and the spatial distortions are critical. If the circumferential region of low pressure is superimposed on the resulting circumferential

region of low temperature, the adverse effect on component stability is reduced; but if the regions are out of phase, the destabilizing effects are compounded (Reference 3). This interaction of pressure and temperature distortions is not well understood and should be investigated as part of future distortion test programs.

3.2 Recommendations for CRF Distortion Testing

Formulation of a distortion test plan requires determination of the aerodynamic patterns and intensities to be tested and the variables to be measured. A general approach has been developed which addresses all foreseeable testing objectives, but the application of this approach should be made in the context of the propulsion system development cycle. If the test article is a preliminary design component for a subsonic aircraft with limited maneuverability (a transport, for example), then a prudent use of testing time and money might be to test only the classical patterns. If, on the other hand, the test article is a full-scale development component for a highly maneuverable supersonic fighter, then it would be a wise investment of testing resources to complete the entire recommended test program. Sound engineering judgment will be required to apply the following recommendations to future test plans.

3.2.1 Aerodynamic Patterns and Intensities

If the compression system component to be tested has an intended service application, and the inlet characteristics of that application are known, testing with the anticipated flight patterns should be given the highest priority once the clean inlet performance mapping has been completed. Should a catastrophic failure occur after this phase of distortion testing is completed, propulsion system development and validation can still proceed. Under these circumstances, discretion should be used to avoid placing too much confidence in the results an incomplete distortion test program.

Because the CRF is does not currently have, and should not develop, the capability to predict aircraft inlet characteristics, it is recommended that the test article

vendor supply these patterns and intensities. Because these flight patterns correspond to maneuvers performed under specific corrected speeds and power settings, it is also recommended that the test article vendor specify the corrected speed at which the patterns be tested.

In addition to the possible airframe-specific patterns, all future CRF test articles should undergo a standardized distortion test program. Application of this test program will allow the development of a database of distortion sensitivities for use in Equation 11 and will allow direct comparison of distortion tolerance between all future test articles.

The amount of distortion testing to be performed will always be a function of the available test time. For this reason, a prioritized test plan is recommended and is presented in Table 1. Unless a catastrophic failure occurs, or is expected to occur as the result of continued testing, **ALL FUTURE CRF TEST ARTICLES SHOULD BE TESTED WITH THE THREE CLASSICAL DISTORTION PATTERNS.**

The circumferential distortion patterns should be rotated relative to the test article to provide no less than 15° resolution of the spatial distortions as they pass through the test article. The number of screen rotations required to implement this recommendation will depend on the actual number of instrumentation rakes installed on the test article.

Table 1. Prioritized Distortion Test Plan

Priority	Distortion Pattern	Intensity (%)	Corrected Speeds (%)
Only if known	Aircraft specific	Supplied by test article vendor	Supplied by test article vendor
1	180° 1/rev* Hub-radial Tip-radial	10 5 5	100, 80, 60 100, 80, 60 100, 80, 60
2	180° 1/rev + Hub-radial* 180° 1/rev + Tip-radial* 90° 1/rev + Hub-radial* 90° 1/rev + Tip-radial*	10 + 5 10 + 5 10 + 5 10 + 5	100, 80, 60 100, 80, 60 100, 80, 60 100, 80, 60

* The circumferential patterns should be rotated relative to the test article to provide a minimum of 15° angular resolution of the flow within the test article.

Because the hub-radial and tip-radial patterns have no circumferential variations, it is not recommended that these patterns be rotated relative to the test article. The composite patterns should be a simple combination of 10% circumferential distortion and 5% radial distortion.

3.2.2 Aerodynamic Measurements

The aerodynamic measurements required for distortion testing are not significantly different than for clean inlet performance mapping, although higher internal resolution of the flow is desired. The test article inlet flow field should be measured using the rake/probe array described in Section 2.2. Time-averaged total pressure and total temperature should be recorded at each of the 40 locations.

Time-averaged total pressure and total temperature should be recorded on the leading edge of each stator row, at the centroids of five equal areas. For test articles with an inlet guide vane row, the inlet rake/probe array should be mounted on the IGVs. For circumferential distortion patterns, the fixed instrumentation should be combined with screen rotations to provide no less than 15° angular resolution of the flow. For pure hub-radial and pure tip-radial distortion patterns, there should be no less than three rakes per stage.

It is desirable to use the exit rake/probe array described in Section 2.2 to record time-averaged total pressure and total temperature downstream of the last stator row. Unfortunately, the stator wakes could potentially render large amounts of this instrumentation meaningless. Sound engineering judgment must be used to locate the array far enough downstream to reduce wake interference, but not so far that duct losses become significant. Because the leading edge of the stator row will be properly instrumented, use of a 40-element exit plane array is not critical as long as the instrumentation used is sufficient to provide proper mass-averaged performance.

3.2.3 Aeromechanic Measurements

In addition to the recording of aerodynamic performance variables, appropriate aeromechanic measurements should be made to ensure that test article health is not compromised. Because the critical blade and/or vane vibration modes vary significantly among test articles, it is not feasible to recommend one strain gauge configuration or another for all future test articles. Sound engineering judgment must be used in the application and monitoring of test article strain gauges.

4 Distortion Generation Hardware

Several methods of producing steady-state and time-variant distortion were investigated for possible use in the CRF. The hardware systems were evaluated on the bases of cost, system flexibility, compatibility with existing CRF facilities, and industry acceptance. A recommendation is made for the hardware to be used for future CRF distortion testing, and the total cost of the full distortion test program recommended in Section 3.2 is estimated.

4.1 Time-Variant Distortion

Although the vast majority of distortion testing has been performed with steady-state distortion patterns, hardware capable of producing time-variant distortion was investigated to determine if it might be suitable for use in the CRF. Although it was determined that use of the devices presented in this section should not be pursued at the CRF, they are presented for completeness.

4.1.1 Planar Pressure Pulse Generator

A schematic view of a planar pressure pulse generator is shown in Figure 7. The device consists of 2 massive solid disks wiih matching holes. One disk is rotated while the other remains fixed, and the test article downstream pulls air through the disks. When the holes in the disks are aligned, air flows freely and the pressure downstream of the device is relatively high; when the holes are not aligned, the flow is restricted and the downstream pressure is reduced.

This device operates at one discrete frequency, although that frequency can be controlled by changing the rotational speed of the disks; the magnitude of the pressure pulse is controlled by changing the distance between the disks. This device generates a negligible amount of steady-state distortion, so the use of screens (or similar device) is

required if steady-state distortion patterns are to be superimposed on the planar pressure pulses. Because the significant vibrations generated by the pressure pulses are transmitted to the facility, it is believed that use of this device at the CRF would require major modifications to avoid causing structural damage to the existing facilities.

4.1.2 Random Frequency Generators

Two types of random frequency pressure distortion generators were investigated and they are shown in Figures 8 and 9. Both are designed to generate turbulence, and the use of screens (or similar device) is required to superimpose a steady-state distortion pattern on the flow. The 2-dimensional random frequency generator (RFG) consists of variable ramps which form the upper and lower walls of a rectangular channel and turbulence is created by boundary layer separation in the channel; the amount of turbulence generated is controlled by changing the positions of the ramps. This type of distortion generator is intended to approximate the length/volume characteristics of a particular aircraft inlet and is not suitable for general distortion testing.

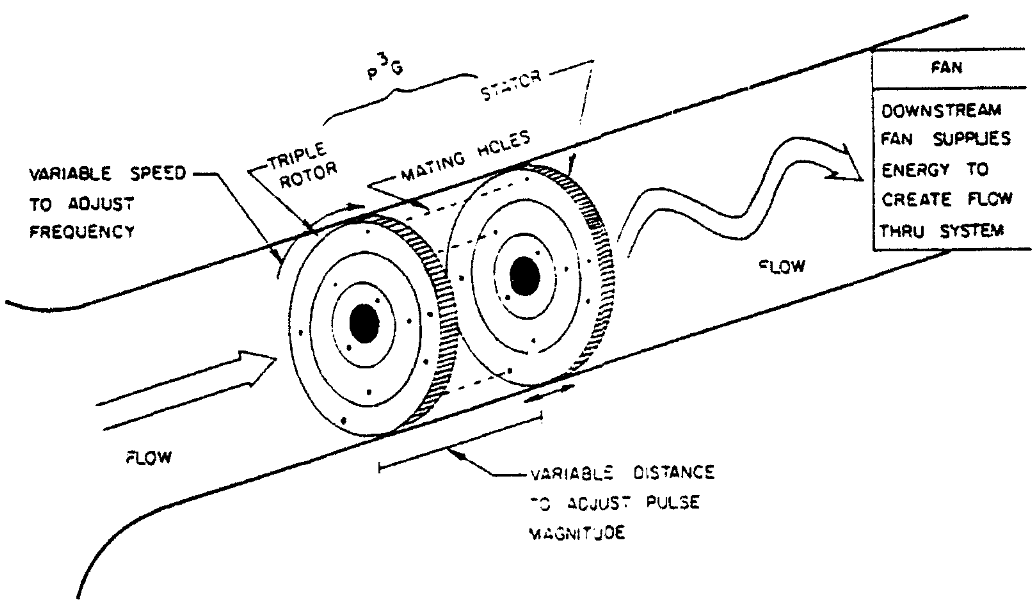

Figure 7. Planar Pressure Pulse Generator

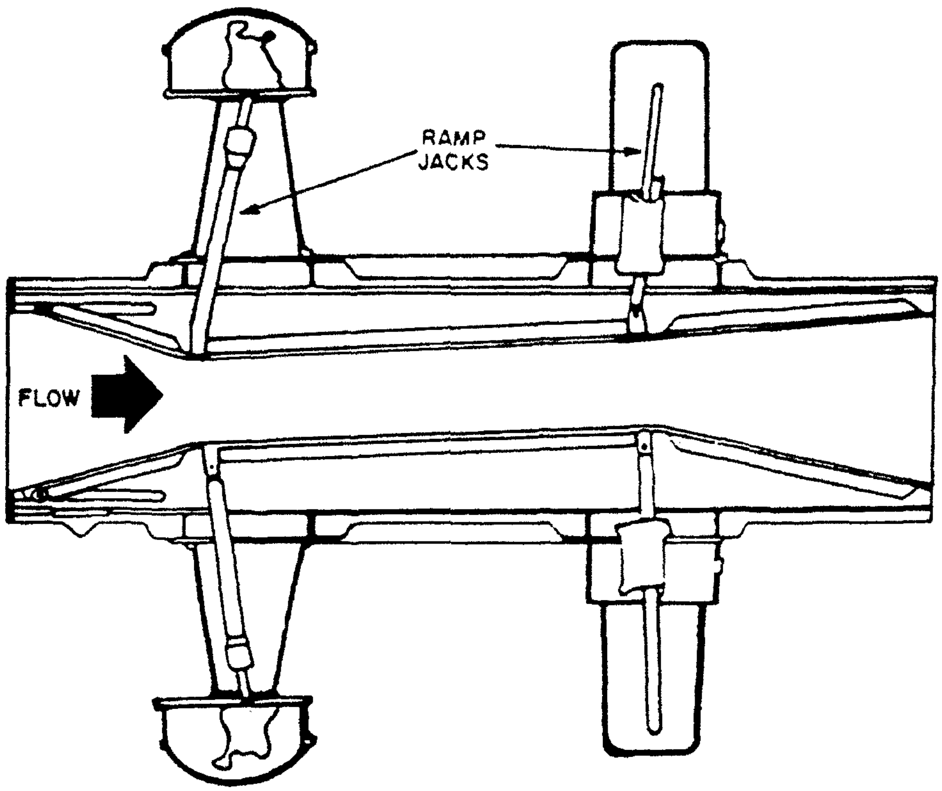

Figure 8. Two-Dimensional Random Frequency Distortion Generator

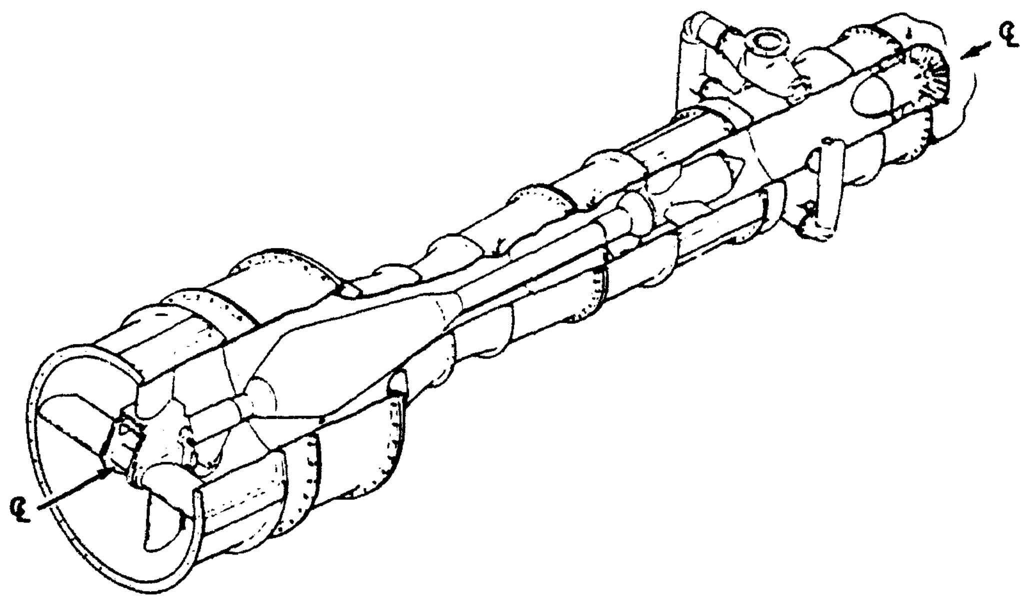

Figure 9. Choked Plug Random Frequency Distortion Generator

The choked-plug RFG consists of a circular converging-diverging channel with a centerbody obstruction, and turbulence is generated by shock-boundary layer interaction. The centerbody obstruction can be translated from the channel axis to create a limited range of asymmetric patterns, but this type of device is not sufficiently flexible for general distortion testing.

4.1.3 Free-Jet Inlet Simulator

A free-jet inlet simulator is shown in Figure 10. A secondary air supply is used to provide flight speed and altitu. airflow over a full-scale inlet. In addition to generating steady-state flight distortion patterns, the orientation of airflow upstream of the inlet can be changed to simulate anticipated aircraft maneuvers. The typical application for this type of testing is full-scale engine/inlet compatibility assessment. The prohibitively expensive secondary air supply and the uniqueness of the aircraft inlet make this system unsuitable for CRF testing.

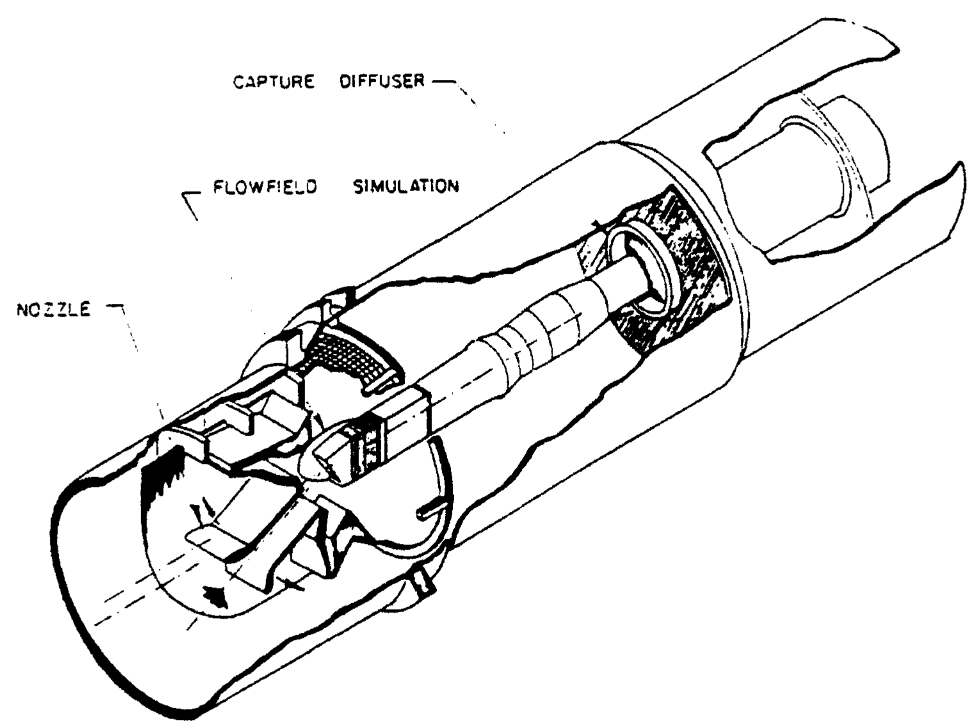

Figure 10. Free-Jet Inlet Simulator

4.2 Steady-State Distortion Hardware

Because time-variant distortion testing is typically directed at a specific engine and aircraft combination, CRF resources should continue to be used to perform steady-state distortion testing. The two devices currently used to generate steady-state distortion patterns are screens and airjet distortion generators, and each is discussed in the following sections.

4.2.1 Distortion Screens

The most commonly used method for creating steady-state pressure-distortion patterns has been the use of screens. These are simply wire mesh of various porosity secured to a sturdy frame and placed approximately one engine diameter upstream of the AIP. The obvious advantages of screens are low cost and simple fabrication. Although each screen is designed for a single mass flow and distortion pattern, it is possible to create complex patterns with typically $\leq 1\%$ turbulence level at the design condition (Reference 4).

There are several disadvantages of this system, however. It takes approximately 12 working days to design, fabricate, and calibrate a distortion screen with an acceptable pattern quality (Reference 5). Distortion screens are physically the same size as the AIP, so each test article will generally require screens designed specifically for that hardware. Because a screen has a single design mass flow and distortion pattern, the distortion which can be expected at other mass flows must be obtained from a calibration curve similar to that shown in Figure 11. The useful range of mass flows for a single screen is limited, and this is undesirable if the test objective is to create the same distortion intensity over a wide range of mass flows. (This is desirable when testing a flight pattern, however, because the distortion varies with mass flow in much the same way as the aircraft inlet performance varies with mass flow.) If it is desired to test multiple intensities or patterns, the screens must be changed offline.

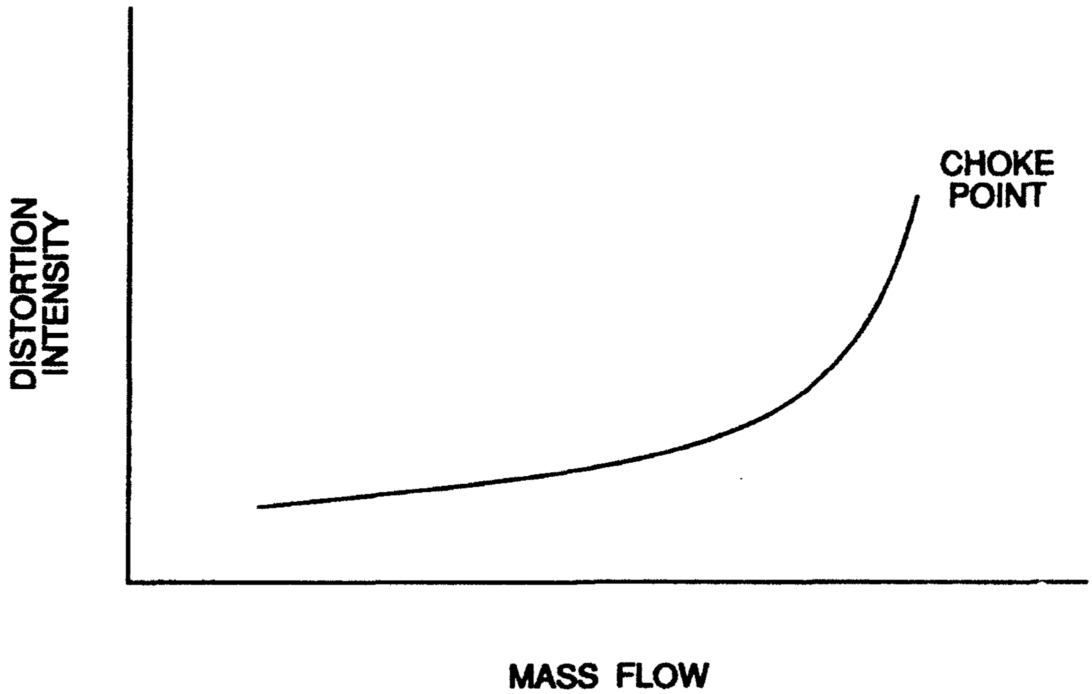

Figure 11. Typical Distortion Screen Calibration Curve

4.2.2 Airjet Distortion Generator

An airjet distortion generator (ADG) produces distortion patterns by forward injection of secondary air (in the opposite direction of air entering the engine) at selected spatial locations, as shown in Figure 12. The momentum of a local region of primary flow is canceled by the injected secondary air, and the associated flow losses create local total-pressure defects. In addition to generating steady-state total-pressure distortion, an ADG has been used to generate planar pressure pulses, and could theoretically be controlled to generate random frequency distortions. Because it has been determined that time-variant distortion testing is beyond the scope of the CRF mission, these factors were not considered in the recommendation of hardware to generate steady-state distortion.

The major advantage of ADG system is flexibility (Reference 5). Once the system has been installed in the test facility and calibrated, it is possible to generate multiple patterns and multiple intensities online; it typically takes between 1 and 2

minutes to stabilize a new pattern. With the secondary airflow turned off, the system produced nominally 0.5% distortion intensity at a corrected airflow of 200 lb_m/s. The system has been shown to create consistent classical patterns, with less than 2.5% overall pattern error, over a wide range of mass flows (160 to 240 lb_m/s corrected).

The major disadvantages of an ADG are complexity, cost, and turbulence. A significant amount of facility support equipment is required to generate the pressurized and temperature conditioned secondary flow needed to operate this system. Based on the assumption that an existing ADG could be provided by AEDC on long-term loan, it is estimated that it would cost approximately $700K to provide the pressurized air supply from building 18 to the test chamber, the secondary air temperature conditioning system, and the air injection control system (Reference 6). Further, the hardware that must be the same physical size as the test article inlet requires approximately 1,000 to 1,500 man-hours to fabricate (Reference 7). It is also questionable whether an ADG system is physically compatible with the existing CRF test chamber.

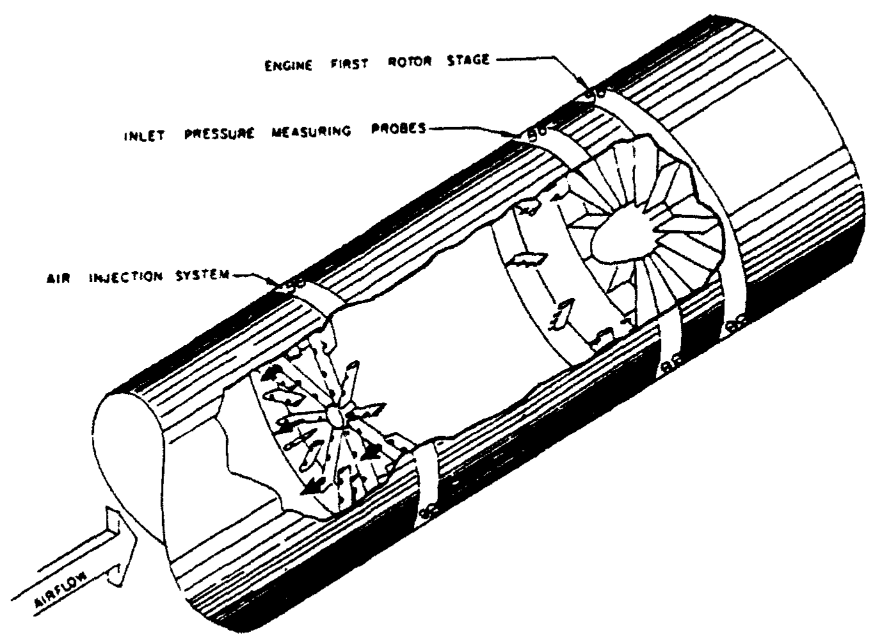

Figure 12. Airjet Distortion Generator

When generating complex distortion patterns with an ADG, or patterns with high intensity, there is significant turbulence in the regions between the secondary air mixing and nonmixing zones. Because this turbulence level is higher than the level a screen would produce, compression system surge margin will be less when tested with an ADG than when tested with screens, and additional stability accounting is required to quantify this effect. Since the ADG and the screen produce roughly the same steady-state pattern, and better stability will be measured when testing with a screen, the ADG system is not accepted by industry for qualification testing.

4.3 Cost Comparison of Screens and ADG

A major factor in every program is cost. As part of the hardware evaluation, a cost comparison of testing with screens vs. testing with an ADG was made. Because most of the fans tested in the CRF to date have had a fairly narrow range of mass flows and physical sizes, and the cores have had a different narrow range, it was assumed that one set of ADG secondary air injection rakes could be used for fan tests and another set for core tests. By proceeding under this assumption, the only significant cost for the ADG system is the initial $700K installation cost. Because the test article vendor has always supplied the distortion screens for CRF testing, the cost to the CRF for screen design and calibration is neglected.

The time required for the ADG system to generate a new distortion pattern is approximately 2 minutes, and is neglected for this comparison. To generate a new distortion pattern with screens, however, requires the screens to be changed offline; each screen change requires approximately 1 hour of down-time for a fan and up to 4 hours for a core. Because a positioning system is available to rotate distortion screens online, the time required to rotate the circumferential patterns is neglected.

It currently costs approximately $15K per day to operate the CRF (Reference 8). Based on the recommended distortion test plan presented in Section 3.2, it is assumed

that all future CRF distortion tests will require eight patterns to be tested. (This is comparable to the number of screens used in previous CRF distortion test programs.) It is further assumed that all screen changes will be made during the test period (as opposed to changing the screens in the morning and testing at night).

The cost to change distortion screens for a fan test is:

$$8\,\text{screens} \times \frac{1\,\text{hr}}{\text{screen}} \times \frac{1\,\text{day}}{8\,\text{hr}} \times \frac{\$15\text{K}}{\text{day}} = \$15\text{K}$$

The cost to change distortion screens for a core test is:

$$8\,\text{screens} \times \frac{4\,\text{hr}}{\text{screen}} \times \frac{1\,\text{day}}{8\,\text{hr}} \times \frac{\$15\text{K}}{\text{day}} = \$60\text{K}$$

Of the previous CRF test articles, 80% were fans and 20% were cores; the current CRF 5-year plan indicates a similar ratio for future tests. Based on this mix, the cost of changing distortion screens for a "generic" future CRF test article is:

$$0.8 \times \$15\text{K} + 0.2 \times \$60\text{K} = \$24\text{K}$$

The number of "generic" test articles which would have to be tested to justify the purchase of an ADG system on the basis of cost alone is:

$$\$700\text{K installation} \times \frac{1\,\text{test article}}{\$24\text{K}} \cong 30\,\text{test articles}$$

Based on the current 5-year plan for CRF testing, the length of time required to justify the purchase of an ADG system on the basis of cost alone is:

$$30\,\text{test articles} \times \frac{5\,\text{years}}{7\,\text{test articles}} \cong 22\,\text{years}$$

4.4 Recommendation for CRF Facility Hardware

As mentioned before, the hardware systems were evaluated on the bases of cost, system flexibility, compatibility with existing CRF facilities, and industry acceptance. Distortion screens offer sufficient testing flexibility, are compatible with existing CRF facilities, are relatively inexpensive, and are widely accepted by industry. Although the ADG system is very flexible in theory, it is uncertain whether the system available from AEDC could be physically located in the existing CRF test chamber, the initial installation is extremely expensive, and use of the device is not accepted by industry for qualification testing. For these reasons, it is recommended that the CRF continue to use screens to generate steady-state total-pressure distortion.

4.5 Estimated Cost of Future CRF Distortion Testing

As mentioned in Section 3.2, a distortion test program should be implemented within the context of the overall propulsion system development cycle. The cost of completing the most rigorous distortion test program recommended is presented, and this will provide an estimated upper bound for the cost of CRF distortion testing.

For this estimation, it is assumed that each of the stator rows is instrumented with three pressure and temperature rakes located approximately 120° apart; eight screen rotations will be required to provide the 15° angular resolution of the flow that is recommended for the circumferential patterns. It is further assumed that one speedline will be taken for one flight-pattern screen, and that each speedline will consist of six steady-state data points (SSDPs).

The number of SSDPs required for the flight-pattern speedline in Table 1 is:

$$1\,\text{speedline} \times \frac{6\,\text{SSPDs}}{\text{rotation}} \times \frac{8\,\text{rotations}}{\text{speedline}} = 48\,\text{SSPDs}$$

The number of SSDPs required for the five circumferential patterns recommended in Table 1 is:

$$5\,\text{screens} \times \frac{3\,\text{speedlines}}{\text{screen}} \times \frac{6\,\text{SSPDs}}{\text{rotation}} \times \frac{8\,\text{rotations}}{\text{speedline}} = 720\,\text{SSPDs}$$

The number of SSDPs required for the two pure radial patterns recommended in Table 1 is:

$$2\,\text{screens} \times \frac{3\,\text{speedlines}}{\text{screen}} \times \frac{6\,\text{SSPDs}}{\text{rotation}} \times \frac{1\,\text{rotations}}{\text{speedline}} = 36\,\text{SSPDs}$$

The total number of SSDPs required for this distortion test is:

$$48 + 720 + 36 = 804\ \text{SSDPs}$$

Because relatively little test time will be spent changing variable vane angles, throttle positions, bleed valves, etc., it is assumed that an average data acquisition rate of 40 SSDPs per day can be maintained during this phase of testing. Based on this assumption, the cost of the distortion testing run-time is:

$$804\,\text{SSDPs} \times \frac{1\,\text{day}}{40\,\text{SSDP}} \times \frac{\$15\text{K}}{\text{day}} \cong \$300\text{K}$$

The cost to change screens for a core is:

$$8\,\text{screens} \times \frac{4\,\text{hours}}{\text{screen}} \times \frac{1\,\text{day}}{8\,\text{hours}} \times \frac{\$15\text{K}}{\text{day}} = \$60\text{K}$$

The total (upper bound) cost to perform the most rigorous CRF distortion test program is:

$$\$300\text{K} + \$60\text{K} = \$360\text{K}$$

As mentioned above, this is an upper bound estimate and the actual cost of performing distortion testing will likely be less than this.

5 Conclusions

A review of the hardware required to generate both time-variant and steady-state inlet total-pressure distortion for compression system testing has been conducted. It was determined that time-variant distortion testing is beyond the scope of the CRF mission and that screens should continue to be used to generate steady-state total-pressure distortion patterns at the CRF.

It is recommended that the CRF adopt the Society of Automotive Engineers Aerospace Recommended Practice, ARP 1420, for all nomenclature relating to inlet total-pressure distortion. To obtain the maximum amount of information from distortion testing, additional instrumentation not typically used for clean inlet performance mapping is recommended. The AIP should be fitted with an eight rake by five element combination total pressure and total temperature probe, as described in Section 2.2. The leading edge of each stator row should be instrumented with five element combination total pressure and total temperature probes; the fixed instrumentation should be combined with screen rotations to provide no less than 15° angular resolution of the flow. For pure hub-radial and pure tip-radial distortion patterns, there should be no fewer than three rakes per stage.

A robust distortion testing methodology has been developed for use at the CRF, but this methodology should be applied within the context of the overall propulsion system development cycle. The recommended test program consists of a minimum of three speedlines with the test article subjected to each of three classical patterns, as outlined in Section 3.2; all future CRF test articles should be tested with these patterns. If aircraft-specific patterns and the corresponding test article corrected speeds are provided by the test article vendor, they should be given high test priority. If sufficient test time is available, three speedlines should be taken with each of four composite

patterns as well. The upper-bound cost estimate to complete this extensive distortion testing program is $360K.

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